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**LABORATORY EVALUATION AND APPLICATION OF
MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED
CONDITIONS FOR PLANETARY ATMOSPHERES**

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I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occultation experiments and earth-based radio astronomical observations can be used to infer abundances of microwave absorbing atmospheric constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. Steffes and Eshleman (1981) showed that under environmental conditions corresponding to the middle atmosphere of Venus, the microwave absorption due to atmospheric SO_2 was 50 percent greater than that calculated from Van Vleck-Weiskopff theory. Similarly, results obtained for the microwave opacity from gaseous H_2SO_4 under simulated Venus conditions, during the first two years of Grant NAGW-533, showed that not only was the opacity from H_2SO_4 much greater than theoretically predicted, but that its frequency (wavelength) dependence was far different than that theoretically predicted (Steffes, 1985 and Steffes, 1986). More recently, measurements made by Steffes and Jenkins (1987), during the third year of Grant NAGW-533, have shown that the microwave opacity of gaseous ammonia (NH_3) under simulated Jovian conditions does indeed agree with theoretical predictions at wavelengths longward of 1.3 cm. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a

range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

In some cases, new observations or experiments have been suggested by the results of the laboratory measurements. For example, this facility was initially developed, and then operated, in order to evaluate the microwave absorbing properties of gaseous sulfuric acid (H_2SO_4) under Venus atmospheric conditions. The results, obtained at 13.4 cm and 3.6 cm wavelengths, were applied to measurements from Mariner 5, Mariner 10, and Pioneer-Venus Radio Occultation experiments, to determine abundances of gaseous sulfuric acid in the Venus atmosphere, with accuracies exceeding those achieved with in-situ instruments (Steffes, 1985). Later efforts concentrated on making laboratory measurements of the microwave absorption from gaseous H_2SO_4 at wavelengths from 1.3 to 22 cm under simulated Venus conditions. We applied these results to radio astronomical observations of Venus which have been made in the same wavelength range, in order to better model the structure of H_2SO_4 and SO_2 abundance in the Venus atmosphere, and to resolve temporal variations of their abundances on a planet-wide basis. The results of this effort were especially rewarding in that the unique frequency and pressure dependences measured for the absorption from gaseous H_2SO_4 in these wavelength ranges has finally explained what were thought to be inconsistencies between measurements of the absorption in the Venus atmosphere at 13.3 and 3.6 cm wavelengths and those

obtained in the 1 to 2 cm wavelength range. Our laboratory measurements also suggested that a substantial variation in the Venus microwave emission, related to the abundance of gaseous sulfuric acid, might exist near the 2.2 cm wavelength. Since no observations of the Venus emission at this wavelength have ever been published, we conducted observations of Venus using the 140-foot NRAO telescope and the 64-meter DSN/Goldstone antenna in April 1987 to not only search for the presence of the predicted feature, but to use such a feature to determine a planet-wide average for sulfuric acid vapor abundance below the main cloud layer. The results of this observation are substantial in that they not only place limits on the abundance and spatial distribution of gaseous H_2SO_4 and SO_2 , but they also suggest some long term temporal variations for the abundance of these two gases. We hope to obtain further confirmation of these variations through reduction and analysis of recently obtained Pioneer-Venus radio occultation measurements. This observation and its results are discussed in Section V of this report. It should be noted that results of our laboratory measurements of the microwave absorption from gaseous H_2SO_4 have also stimulated new studies of the theoretical basis for H_2SO_4 opacity (see Section V).

An equally important activity for this grant year has continued to be laboratory measurements of the microwave and millimeter-wave properties of the simulated atmospheres of the outer planets and their satellites. As described in the previous Annual Status Report for Grant NAGW-533 (February 1, 1986 through January 31, 1987), initial laboratory measurements of the microwave opacity of gaseous ammonia (NH_3) in a hydrogen/helium (H_2/He) atmosphere, under simulated conditions for the outer planets were completed in September 1986. These measurements were conducted at frequencies from 1.3 GHz to 22 GHz

(wavelengths from 1.3 cm to 22 cm), at temperatures from 178 K to 300 K, and under total pressures reaching as high as 6 atmospheres. Such measurements have long been sought by a number of researchers working on inferring ammonia abundance profiles in Jovian atmospheres. Our measurements represented the first time that measurements of the microwave absorption of gaseous ammonia under simulated conditions for the outer planets had been conducted. The results of these measurements, and their effect on the interpretation of microwave opacity data from Jupiter, obtained both from Voyager radio occultation measurements made at 13 cm and 3.6 cm wavelengths and from radio astronomical observations in the 1.3 cm to 20 cm wavelength range, are discussed in a paper entitled "Laboratory Measurements of the Microwave Opacity of Gaseous Ammonia (NH_3) Under Simulated Conditions for the Jovian Atmosphere," by Steffes and Jenkins (1987), which was recently published in Icarus (September 1987). These results showed that in the 1.38 to 18.5 cm wavelength range, the absorption from gaseous ammonia was correctly expressed by the modified Ben-Reuven lineshape as per Berge and Gulkis (1976). As a result, it became clear that the opacity which would be exhibited by a solar abundance of ammonia would be a factor of 1.5-2.0 below the opacity at the 2 to 6 Bar levels of the atmosphere as inferred from radio emission studies in the 6 to 20 cm wavelength range (see de Pater and Massie, 1985 and de Pater, 1986), and the opacity at the 1 Bar level measured by the Voyager 13 cm wavelength radio occultation experiment (see Lindal et al., 1981). This additional opacity, while most likely due to an overabundance of gaseous ammonia beyond the solar abundance, might also have been due to other gases or condensates, especially in the 2 to 6 Bar levels of the atmosphere.

As a result, in this current grant year, we have continued laboratory measurements of the microwave absorption and refraction from other potential microwave absorbers contained in the outer planets' atmospheres, including methane (CH_4) and water vapor (H_2O), as well as additional high-sensitivity measurements of the absorption from gaseous NH_3 at 13.3 and 18.5 cm (results are presented in Section IV). It has also been brought to our attention by several researchers that significant uncertainties exist as to the actual absorption spectrum of gaseous ammonia at wavelengths shortward of 1 cm. It has been found by some (e.g., de Pater and Massie, 1985) that the observed millimeter-wave emission from Jupiter is inconsistent with the millimeter-wave absorption spectrum predicted using the modified Ben-Reuven line shape for ammonia. In order to confirm this, we have developed a Fabry-Perot spectrometer system capable of operation from 30 to 41 GHz (wavelengths from 7.3 to 10 mm). This system can be used at pressures up to 2 Bars and temperatures as low as 150 K, which corresponds closely to the conditions at altitudes in the Jovian atmosphere most responsible for the observed millimeter-wave absorption. A complete description of the millimeter-wave spectrometer is given in Section II.

We have used this spectrometer to complete laboratory measurements of the 7.5-9.3 mm absorption spectrum of ammonia, as well as additional measurements of CH_4 . The results of these measurements (presented in Section IV) are substantive in that they show that neither the modified Ben-Reuven lineshape nor the Van Vleck-Weisskopf lineshape best describe the 7.5-9.3 mm (32-40 GHz) absorption from gaseous NH_3 under simulated Jovian conditions. Since even larger variations from theoretically-derived opacity values can be expected at shorter millimeter-wavelengths (see de Pater and Massie, 1985), we hope to

pursue further laboratory measurements at short millimeter-wavelengths, especially near 3.2 mm (94 GHz), where a large number of observations of the emission from the outer planets have been made. A better knowledge of the millimeter-wave absorption properties of NH_3 is essential, not only to help better characterize the distribution and abundance of ammonia at high levels in Jovian atmospheres, but to make it possible to resolve the contributions from other absorbing constituents such as H_2S (see Bezard et al., 1983). We also intend to investigate the further improvement of the sensitivity/accuracy of our existing systems (1.3 to 18.5 cm and 7.5 to 10 mm) through the integration of high temperature superconducting materials into the resonators. A more complete discussion of this proposed future activity is included in the accompanying proposal to NASA entitled, "Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres."

Of equal importance, however, will be the further analysis of microwave absorption data from Venus and the application of our laboratory results for the microwave absorption from gaseous SO_2 and gaseous H_2SO_4 in the Venus atmosphere to that data. As discussed in Section V, our recent measurements of the Venus microwave emission at 2.25 cm and 1.9 cm made with the NRAO 140-foot telescope, and at 3.6 cm and 1.35 cm made with the DSN (Goldstone) 64-meter antenna have shown that substantial spatial or temporal variations in the abundance and distribution of gaseous H_2SO_4 and SO_2 are likely to be occurring in the Venus atmosphere. An effective tool for evaluating spatial variations in the abundance of these microwave absorbing gases is the radio occultation studies which are conducted with the Pioneer-Venus orbiter. It is our hope to be active in the reduction and interpretation of the Pioneer-Venus

radio occultation data obtained in the Winter 1986/87 time period, both for determining spatial variations in sulfur-bearing gas abundances, and for determining temporal variations by comparison with previously obtained data. A more complete description of our proposed involvement in this activity is included in the accompanying proposal.

II. THE GEORGIA TECH RADIO ASTRONOMY AND PROPAGATION (R.A.P.) FACILITY

The basic configuration of the planetary atmospheres simulator developed at Georgia Tech for use in measurement of the microwave absorptivity of gases under simulated conditions for planetary atmospheres is described at length in the previous Annual Status Report(s) for Grant NAGW-533. It is also discussed at length in Steffes (1986) and Steffes and Jenkins (1987). The updated simulator system, shown in Figure 1, is currently configured for simulations of the outer planets. Measurements of the microwave opacity and refractivity of test gas mixtures can be performed at frequencies from 1.6 GHz to 27 GHz (wavelengths from 1.2 cm to 18.5 cm) using two microwave resonators contained within a pressure chamber. While the pressure chamber itself is capable of containing pressures up to 10 atmospheres, and the temperature chamber is capable of achieving temperatures as low as 150 K, it has been found that the combination of high pressures and low temperatures can create a substantial problem with sealing the pressure chamber. The use of gaseous hydrogen (H_2) in the outer planets simulations has required the development of procedures and equipment for conducting such simulations. In addition, a thermocouple vacuum sensor is included in the system. This sensor not only allows accurate determination of pressure vessel evacuation, but it can also be used for accurately determining the abundances of microwave-absorbing test gases, which

are typically very small at low temperatures, due to low saturation vapor pressures.

The overall result has been a pressure vessel large enough to contain two microwave resonators, which is capable of maintaining 6 atmospheres of pressure at a temperature of 150 K, with an acceptably small leak ratio. While the range of pressures which can be tested was not quite as large as originally hoped, the resulting range of temperatures and pressures does represent the range over which nearly all of the microwave opacity in the Jupiter atmosphere has been observed, and thus is extremely useful in interpretation of microwave opacity data from Voyager I and II radio occultation experiments, as well as from earth based radio astronomical observations, and, in the future, opacity measurements to be made using the Galileo probe. Likewise, the pressure-temperature ranges measured are close enough to those over which microwave absorption or refraction has been measured in the atmospheres of Saturn, Titan, Uranus, and Neptune, so that accurate estimates of abundances of microwave-absorbing constituents in these atmospheres can also be made.

The most recent addition to the Georgia Tech Radio Astronomy and Propagation Facility has been a Fabry-Perot type resonator capable of operation between 30 and 41 GHz. As shown in Figure 2, the resonator consists of two gold plated mirrors separated by a distance of about 20 cm. The mirrors are contained in a T-shaped glass pipe which serves as a pressure vessel capable of withstanding over 2 atm of pressure. Each of the three open ends of the pipe is sealed with an O-ring sandwiched between the lip of the glass and a flat brass plate which is bolted to an inner flange. Electromagnetic energy is coupled both to and from the resonator by twin irises located on the

surface of one of the two mirrors. Two sections of WR-28 waveguide which are attached to the irises pass through the brass plate to the exterior of the pressure vessel. The end of each waveguide section is pressure-sealed by a rectangular piece of mica which is held in place by a mixture of rosin and beeswax. As shown in Figure 3, one of these ends is connected to the sweep oscillator through a waveguide section. A Ka-band (26-40 GHz) mixer is attached to the other section of waveguide and is coupled to the high resolution spectrum analyzer through a calibrated section of coaxial cable. The entire resonator, including its glass pressure envelope, is placed in the temperature chamber, which is a low-temperature freezer capable of operation down to 150 K. A network of stainless steel tubing and valves connects other components such as gas storage tanks, vacuum gauges, the pressure gauge, and the vacuum pump to the resonator assembly, so that each component may be isolated from the system as necessary. When properly secured, the system is capable of containing up to two atmospheres of pressure without detectable leakage. The sensitivities (minimum detectable opacities) achievable with this system are shown in Figure 4. It should be noted, however, that improvements of several orders of magnitude could be achieved if superconducting materials could be placed on the surfaces of the mirrors in the resonator.

III. EXPERIMENTAL APPROACH

The approach used to measure the microwave absorptivity of test gases in an H_2/He atmosphere is similar to that used previously by Steffes and Jenkins (1987) for simulated Jovian atmospheres. At frequencies below 22 GHz (see Figure 1), the absorptivity is measured by observing the effects of the introduced gas mixture on the Q, or quality factor, of two cavity resonators

at particular resonances from 1.62 GHz to 21.8 GHz. At frequencies between 30 and 41 GHz, the changes in the Q of the numerous resonances of the Fabry-Perot resonator (see Figure 3) are related to the absorptivity of the test gas mixture at these frequencies. The changes in the Q of the resonances which are induced by the introduction of an absorbing gas mixture can be monitored by the high resolution microwave spectrum analyzer, since Q is simply the ratio of the cavity resonant frequency to its half-power bandwidth. For relatively low-loss gas mixtures, the relation between the absorptivity of the gas mixture and its effect on the Q of a resonance is straightforward:

$$\alpha \approx (Q_L^{-1} - Q_C^{-1})\pi/\lambda \quad (3)$$

where α is absorptivity of the gas mixture in Nepers km^{-1} . (Note, for example, that an attenuation constant or absorption coefficient or absorptivity of 1 Neper $\text{km}^{-1} = 2$ optical depths per km (or km^{-1}) $= 8.686 \text{ dB km}^{-1}$, where the first notation is the natural form used in electrical engineering, the second is the usual form in physics and astronomy, and the third is the common (logarithmic) form. The third form is often used in order to avoid a possible factor-of-two ambiguity in meaning.) Q_L is the quality factor of the cavity resonator when the gas mixture is present, Q_C is the quality factor of the resonance in a vacuum, and λ is the wavelength (in km) of the test signal in the gas mixture.

The first experiments involved high-sensitivity measurements of the microwave absorption from gaseous NH_3 under simulated conditions for the 2 to 6 Bar pressure range of the Jovian atmosphere in the 10 to 20 cm wavelength range. These measurements were undertaken in order to help better explain the

source of the microwave opacity at altitudes below the 2 atm pressure level in the Jovian atmosphere. (See Steffes and Jenkins, 1987, or the previous Annual Status Report for Grant NAGW-533, for further discussion.) These measurements were conducted at 1.62 GHz (18.5 cm) and 2.25 GHz (13.3 cm), and took advantage of special adjustments to the atmospheric simulator so as to maximize sensitivity in the 10 to 20 cm wavelength range.

Temperatures from 193 K to 300 K were used for the experiments, since lower temperatures would risk condensation of the gaseous NH_3 . When the pressure vessel reached thermal stability at the desired temperature, which was monitored using both the temperature sensors and the resonant frequencies of the system, a vacuum was drawn in the pressure vessel containing the resonators, and the bandwidth and center frequency of each of resonances was then measured. A valve was then opened which allowed the ammonia gas to enter the chamber, where 17 torr NH_3 pressure was used. Measurements of the gaseous NH_3 pressure were made with the high accuracy thermocouple vacuum gauge tubes which are shown in Figure 1. Next, 5.4 atm of hydrogen (H_2) and 0.6 atm of helium (He) were added. These gases were admitted to the chamber at a sufficiently slow rate so as not to significantly affect the temperature within the chamber. The result was an atmosphere with 6 atm total pressure composed of 90 percent hydrogen, 10 percent helium, and approximately 3730 ppm ammonia. The bandwidth of each resonance was then measured and compared with its value when the chamber was evacuated in order to determine the absorptivity of the gas mixture at 6 atm total pressure. The total pressure was then reduced by venting to 4 atm, and the bandwidths were again measured. Subsequent measurements were likewise made at 2 atm pressure. The pressure vessel was then evacuated and the bandwidths again measured so as to assure no

variation (either due to thermal shift or chemical reaction) of the Q's of the evacuated resonators had occurred. The measured changes of bandwidth (Q) were then used to compute the absorptivity of the gas mixture under the various pressure conditions.

This approach has the advantage that the same gas mixture is used for the absorptivity measurements at the various pressures. Thus, even though some small uncertainty may exist as to the mixing ratio of the initial mixture, the mixing ratios at all pressures are the same, and thus the uncertainty for any derived pressure dependence is due only to the accuracy limits of the absorptivity measurements, and not to uncertainty in the mixing ratio. (This assumes that the mixing ratio is small, so that foreign-gas broadening predominates, as is the case for our measurements.) Similarly, measurements of the frequency dependence of the absorptivity from the mixture would likewise be immune to any mixing ratio uncertainty, since foreign-gas broadening predominates.

The second major set of experiments involved measurements of the microwave absorption from methane (CH_4) under simulated Jovian conditions at frequencies from 2.2 to 21.7 GHz. These experiments employed the same dual-cavity atmospheric simulator as was used for the earlier ammonia experiments, shown in Figure 1. However, since methane absorption is very low, much larger methane mixing ratios were required to achieve detectable levels of absorption at these wavelengths. Likewise, since the methane absorption is inversely proportional to temperature, the lowest possible temperatures were used so as to maximize measurable absorption. In contrast to ammonia, the saturation vapor pressure of methane is quite large, thus risk of condensation was not a consideration. As a result, absorption from pure methane at pressure up to

6 Bars and at a temperature of 153 K was measured, as well as absorption from a 40% methane, 52% hydrogen, and 8% helium atmosphere under the same conditions of temperature and pressure. These measurements were made using resonances at 2.25 GHz (13.3 cm), 8.52 GHz (3.5 cm), and 21.7 GHz (1.38 cm).

The third set of measurements were made at the same frequencies, but involved measurements of the microwave absorption of water vapor under simulated Jovian conditions. Because of the relatively low saturation vapor pressure of water, experiments were conducted at 300 K, in order to obtain sufficient water vapor for the experiment. As with the previous experiments, the dual-cavity atmospheric simulator, shown in Figure 1, was used. A major difference, however, was the source of the test gas, in this case, H_2O . Since pressurized cannisters of water vapor are not possible at room temperature or lower, a flask of liquid H_2O was used as the source of water vapor. Using techniques similar to those used by Steffes (1985 and 1986) for measurement of the microwave absorption from gaseous H_2SO_4 , a precise quantity of water vapor was obtained. That is, the flask is filled with a precisely known volume of distilled water. A vacuum is then drawn in the pressure vessel containing the microwave resonators, and the bandwidth and center frequencies of the resonances are then measured. A valve is then opened which allows the water vapor eluting from the flask to fill the evacuated pressure vessel (0.031 m^3 of open volume with the resonators in place) and reach vapor pressure equilibrium with the liquid H_2O . Note that all components which contact the water vapor are maintained at the same temperature as the flask, so as to avoid condensation.

As H_2O vapor fills the chamber, changes in the resonance center frequencies are observed. These changes are related to the H_2O vapor abundance. After approximately 10 minutes, the frequency shift ceases, as vapor pressure

equilibrium is reached. The valve to the reservoir flask is then closed, and 5.4 atm of H_2 and 0.6 atm of He are admitted to the chamber containing the H_2O vapor. The bandwidth of each response is then measured and compared with its value when the chamber was evacuated in order to determine the absorptivity of the gas mixture at 6 atm total pressure. The total pressure is then reduced by venting, and the bandwidths are again measured. Subsequent measurements are likewise made at lower pressures in order to determine absorptivities at those pressures. The pressure vessel is then evacuated and the bandwidths again measured so as to assure no variation (either due to thermal shift or chemical reaction) of the Q's of the evacuated resonators has occurred. After the experiment is complete, the volume of the remaining liquid is measured and compared with the initial volume measured in order to determine the amount of H_2O vapor present in the gas mixture tested. As with the ammonia experiments, this approach has the advantage that the same gas mixture is used for the absorptivity measurements at the various pressures.

The fourth set of measurements has involved the millimeter-wave absorption from gaseous ammonia (NH_3) in a 90% H_2 /10% He atmosphere. Initial measurements were conducted at room temperature, but the majority of measurements have been conducted at a temperature of 203 K. While even lower temperatures could be achieved, the need to avoid the risk of ammonia condensation kept our operating temperatures relatively high. As in the previous experiments at lower frequencies, the bandwidth and center frequencies of each of several resonances between 32 and 41 GHz were measured in a vacuum. Next, 28 torr of gaseous ammonia is added to the system. The pressure of the ammonia gas is measured with the high-accuracy thermocouple vacuum gauge, as shown in Figure 3.

In addition, the ammonia abundance can be monitored by measuring refractivity of the introduced gas. Since the index of refraction (relative to unity) is proportional to the ammonia gas abundance, the ability of the system to accurately measure refractivity (through measurement of the frequency shift of resonances) can be used to infer the relative vapor abundance or pressure. Note that it is not yet possible to use this approach for the accurate determination of absolute NH_3 pressure since accurate refractivity data for the 7.3 to 10 mm wavelength range is not available. In fact, by using our thermocouple vacuum gauge, we have made measurements of the density-normalized refractivity of gaseous ammonia at 39 GHz, and found it to be 8.8×10^{-17} N-units/molecule/cm, which is nearly 8 times the value at optical wavelengths.

Next, 1.8 atm of hydrogen (H_2) and 0.2 atm of helium (He) are added to the chamber, bringing the total pressure to 2 atm. The bandwidth of each resonance is then measured and compared with its value when the chamber was evacuated in order to determine the absorptivity of the gas mixture at 2 atm total pressure. The total pressure is then reduced, by venting, to 1 atm, and the bandwidths are again measured. Finally, the pressure vessel is again evacuated and the bandwidths again measured so as to assure no variation of the Q's of the evacuated resonator has occurred. As with the previous measurements, the measured changes of bandwidths (Q's) can then be used to compute the absorptivity of the gas mixtures at each of the resonant frequencies.

In all four types of the measurements described, the amount of absorption being measured is extremely small. Thus, any errors in measurements of (or other changes in) the apparent bandwidth of the resonances, not caused by the absorbing gases, could lead to significant errors in the absorption

measurement. The contribution of instrumental errors and noise-induced errors on such absorptivity measurements have been discussed at length in Steffes and Jenkins (1987). However, because our latest measurements represent such small percentage changes in bandwidth, another instrumental source of error which we refer to as dielectric loading becomes a concern.

As can be seen in Figures 1 and 3, the resonators, which operate as bandpass filters, are connected to a signal source (the microwave sweep oscillator) and to a signal receiver (the high-resolution spectrum analyzer). The "Q" of the resonator, which is defined as the ratio of energy stored in the resonator to the energy lost per cycle, equals the ratio of resonant center frequency to resonance half-power bandwidth. It is not surprising, therefore, that the stronger the coupling between the resonator and the spectrum analyzer or sweep oscillator, the lower will be the Q of the resonance, since more energy will be lost per cycle through the cables or waveguide connecting the resonator to the spectrum analyzer and sweep oscillator. For this reason, we have always designed our resonators (both the coaxially-coupled cylindrical cavity resonators used below 25 GHz and the waveguide-coupled Fabry-Perot resonator used above 30 GHz) with minimal coupling, so as to maximize Q and to minimize the changes in Q that might result from changes in coupling that occur when gases are introduced into the resonators. It should be noted that these changes in coupling, which are due to the presence of the test gas mixtures, are not related to the absorptivity of the gases, but rather to the dielectric constant or permittivity of the test gas mixtures. (Hence, the term "dielectric loading.")

We have always strived to design the coupling elements of the resonators so that the changes in lossless test gas abundances (and resulting changes in

dielectric constant) had little or no effect on the Q of the resonator as measured in the system. This has been no small feat in that slight imperfections in resonators, cables, coupling loops, or waveguides can make the apparent Q of the resonator appear to vary with the abundance of such lossless gases. It has now become a standard part of our experimental procedure to repeat absorption measurements for gas mixtures in which the absorbing gas is a minor constituent, without the absorbing gas present. For example, after measurements were made of the microwave and millimeter-wave absorption from ammonia as a minor constituent in an H_2/He atmosphere, measurements of the apparent absorption of the H_2/He atmosphere without the ammonia gas were made. Since, for the pressures and wavelengths involved, the H_2/He atmosphere is essentially transparent, no absorption was expected. If any apparent absorption was detected, "dielectric loading," or a change in coupling due to the dielectric properties of the gases, was indicated.

Initially, if any evidence of dielectric loading existed, the experiments were terminated and the apparatus disassembled, including pressure seals. The cables and coupling loops were then readjusted, and the system reassembled and tested again. The entire procedure was repeated until the dielectric loading effect was eliminated or minimized. If some small variation in the resonant Q or bandwidth due to the presence of the non-absorbing gases still remained, it was added to the uncertainty or error bars for each experiment. More recently however, we have found that the effects of dielectric loading are additive, in that they add to the apparent changes of resonator bandwidth caused by the absorbing gases. Thus, as long as the effects of dielectric loading are not time variable, they can be removed by using the measured value of the Q of a resonance with the non-absorbing gases present (instead of the Q of the resonance in a vacuum) for the quantity Q_c in equation (3).

IV. RESULTS OF LABORATORY MEASUREMENTS AND THEIR APPLICATION

As described in Section III, the first experimental sequence involved measurements of the microwave absorption from gaseous ammonia (NH_3) in a 90% hydrogen/10% helium atmosphere at the frequencies 1.62 GHz (18.5 cm) and 2.25 GHz (13.3 cm). These experiments were conducted with an ammonia mixing ratio of 3730 ppm, at temperatures as low as 193 K, with total pressures up to 6 atm. The results of these measurements are included in Figure 5 along with all of our previous absorptivity measurements for such an ammonia mixture at 193 K. Also shown are plots of the theoretically-derived absorption spectra for such gas mixtures at these three pressures. These theoretically-derived NH_3 absorption spectra were calculated as per de Pater and Massie (1985) and Berge and Gulkis (1976), both of which employ a Ben-Reuven line shape which has been modified so as to be consistent with the laboratory results of Morris and Parsons (1970), in which the absorption from NH_3 in a high-pressure H_2/He atmosphere at room temperature and at 9.58 GHz was measured. Our theoretical spectra have been adjusted for the temperature, pressure, and mixing ratio conditions of our experiment. This mathematical expression for the absorption of ammonia was implemented in a BASIC program for which partial pressures from H_2 , He , and NH_3 , as well as frequency and temperature, were adjustable variables. This program was used to calculate the theoretical values for absorption given in Tables I and II and in Figures 5 and 6.

Inspection of Figure 5 shows that the laboratory data agree surprisingly well with the theoretical predictions for NH_3 opacity made using the Ben-Reuven lineshape, and are, likewise, consistent with the results of Morris and Parsons (1970). The key result of our work has been the finding that the

modified Ben-Reuven lineshape appears to correctly describe the shape of the absorption spectrum from gaseous ammonia in a hydrogen/helium atmosphere in the 1.3 to 18.5 cm wavelength range even under the temperature-pressure conditions characteristic of the Jovian atmosphere. This finding answers some questions and raises others. For example, both de Pater and Massie (1985) and West et al. (1986) recognized that, based on interpretation of the Jovian emission spectrum in the 10 to 20 cm wavelength range using the theoretically-derived absorption spectrum from ammonia, opacity at pressure levels greater than 2 atm had to exceed the amount which would be caused by the solar abundance of ammonia. As a result, both sets of authors concluded that either the theoretical lineshape was incorrect and understated the opacity of ammonia at these wavelengths by a factor of 1.5-2.0, or the ammonia abundance was greater than its solar abundance by a factor of 1.5-2.0 at pressures greater than 2 atm, or that an extra opacity source, possibly H₂O condensate, was present. Thus, since our measurements of the ammonia opacity at 13.3 cm (2.25 GHz) agree quite closely with the theoretically-derived values for opacity, and since our newest results at 18.5 cm (1.62 GHz) are likewise consistent with the theoretical lineshape, it would appear that either the ammonia abundance is greater than solar by a factor of 1.5-2.0 in the deeper layers of the Jovian atmosphere, or that an extra opacity source is present.

In an attempt to resolve this question, we have made measurements of the microwave opacity of two other Jovian atmospheric constituents: methane and water vapor. The methane experiment was conducted as described in Section III, and not surprisingly, the microwave absorption was very small. Measurements were made at 153 K of the microwave absorption from a pure methane atmosphere at 6 atm pressure, and from a 40% methane, 52% hydrogen,

and 8% helium atmosphere at 6 atm pressure. No absorption was measured at the 2.25 GHz (13.3 cm) or 8.52 GHz (3.5 cm) resonances. Some absorption was measured at the 21.7 GHz (1.38 cm) resonance, but its statistical significance is uncertain since the levels measured were below the error bars for the system. (For the pure methane, the measured absorption was 11.4 ± 17 dB/km. For the 40% methane mixture, the measured absorption was 9.4 ± 18 dB/km.) We intend to further study the theoretically-derived methane absorption spectrum for purposes of comparison and to determine whether further laboratory measurements at higher frequencies might be useful. However, the results strongly indicate that methane absorption in the 3-13 cm wavelength range is negligible in the 2-6 Bar pressure range of Jupiter's atmosphere, and cannot account for the additional opacity required in that altitude range.

Measurements of the microwave absorption from water vapor were conducted at 2.25 GHz, 8.52 GHz, and 21.7 GHz at 297 K in a 90% H₂/10% He atmosphere as described in Section III. A water vapor mixing ratio of 3509 ppm was used, and total pressures of 6, 4, and 2 atm were employed. None of the measurements detected statistically significant opacity. (System thresholds were 0.45 dB/km, 0.73 dB/km, and 36 dB/km at 2.25 GHz, 8.52 GHz, and 21.7 GHz, respectively.) Thus our results for the microwave opacity from water vapor (1.38 to 13.3 cm) under simulated Jovian conditions are consistent with the theoretically-based expression for opacity derived by Goodman (1969). Furthermore, our results indicate that, like methane, water vapor cannot account for the additional opacity required in the 2-6 Bar pressure range of Jupiter's atmosphere. Thus, all three of these measurements further strengthen the case for an ammonia abundance between 1.5 and 2.0 times larger than solar abundance.

Initial measurements of the 7.3-8.3 mm absorptivity from NH_3 in a hydrogen/helium atmosphere were conducted at 298 K as described in Section III, with an ammonia mixing ratio of 1.32×10^{-2} , at pressures of 1 and 2 Bars. An examination of the experimental results revealed that because of large error bars, we cannot determine whether the modified Ben-Reuven lineshape best describes the absorption profile of gaseous ammonia shortward of 1 cm. However, the consistency of our results at 2 atm suggested that the modified Ben-Reuven lineshape understates the actual absorptivity of ammonia in this range. With the exception of one measurement at 40.62 GHz, all measurements were greater than those predicted by the Ben-Reuven theory.

Results of measurements of the 32 to 40 GHz (7.5 to 9.2 mm) absorptivity of gaseous ammonia under simulated Jovian conditions (203 K) are shown in Table III and Figure 6. These measurements were made using a 90% hydrogen/10% helium atmosphere with a total pressure of 2 Bars. The ammonia mixing ratio was .018. With this mixing ratio, temperatures as low as 190 K could have been used before saturation would have become a problem, but difficulties with one of the compressors in our ultra-cold freezer system required our operating at a slightly higher temperature. (Funding is currently being procured from within Georgia Tech to provide needed repairs to the freezer, in support of planetary atmospheres research at Georgia Tech.) Also, shown in Figure 6 are solid lines which represent the theoretically-computed opacity using the Van Vleck-Weisskopf lineshape (upper line) and the modified Ben-Reuven lineshape (lower line). The Van Vleck-Weisskopf calculation was performed using linewidths and line intensities as per Wrixon et al. (1971). The Ben-Reuven calculation was made as per Berge and Gulkis (1976), as earlier described.

Inspection of the results in Figure 6 shows that neither lineshape correlates well with all of the observed points. Except for one data point, the opacity measurements between 38 and 40 GHz appear to be in best agreement with the modified Ben-Reuven lineshape, whereas between 35 and 37 GHz, the opacity measurements appear to agree best with the Van Vleck-Weisskopf lineshape. Such results are not surprising in that other researchers, such as de Pater and Massie (1985), have found that in order to best explain the 1-10 mm Jupiter emission spectrum, a different sort of lineshape was needed to characterize the ammonia opacity. For this purpose, de Pater and Massie developed two modified Van Vleck-Weisskopf lineshape characterizations for the ammonia opacity in a hydrogen/helium atmosphere. Since even larger variations from either the modified Ben Reuven formulation or the Van Vleck-Weisskopf formulation for ammonia opacity are expected at shorter millimeter-wavelengths, we hope to pursue further laboratory measurements, especially near 3.2 mm (94 GHz), where a larger number of observations of the emission from the outer planets have been made.

A better knowledge of the millimeter-wave absorption properties of NH_3 is essential, not only to help better characterize the distribution and abundance of ammonia at high levels in Jovian atmospheres, but to make it possible to resolve the contributions from other absorbing constituents such as H_2S (see Bezard et al., 1983). Our goal to better characterize the millimeter-wave absorption spectrum of ammonia will not only involve increasing the range of frequencies over which measurements are made, but to increase the sensitivity of the measuring systems. There are several ways that we may improve the sensitivity of the system and increase the reliability and accuracy of the measurements. The most useful is to increase the signal to noise ratio,

either by increasing the quality factor of the resonator, or by increasing the amount of absorption observed. Both of these can be achieved by performing the experiment at lower temperatures. As the physical temperature of the system decreases, the surface conductivity of the gold on the resonator's mirrors increases, which improves the quality factor of the resonances. However, lowering the operating temperature below 190 K could cause the gaseous ammonia to condense. The only way to further improve the quality factor would be to place superconducting materials on the mirror surfaces. We intend to pursue the possible integration of superconducting materials into our existing systems (microwave: 1.3-18.5 cm and millimeter-wave: 7.5-10 mm). A more complete discussion of this is included in the accompanying proposal, "Laboratory Evaluation and Application of Microwave Absorption Properties under Simulated Conditions for Planetary Atmospheres."

V. OBSERVATIONS OF THE MICROWAVE EMISSION OF VENUS FROM 1.3 TO 3.6 cm

As discussed in Steffes (1986), our previous laboratory measurements of the microwave absorption of gaseous H_2SO_4 under simulated conditions for the Venus atmosphere suggested that the 2-3 cm Venus emission spectrum would be especially sensitive to the subcloud abundance of gaseous H_2SO_4 . Since no observations of the Venus emission in this wavelength range have ever been published, we conducted observations using the NRAO 140-foot radio telescope in order to search for spectral features related to gaseous H_2SO_4 abundance. Also, since apparent temporal variations in the Venus microwave emission spectrum from 1.3 to 3.6 cm have occurred, it was felt that simultaneous, or nearly simultaneous, measurements over that entire wavelength range would best

serve our need to characterize both the magnitude and the shape of the microwave emission spectrum of Venus, with the ultimate goal of inferring abundances and distribution of the microwave absorbing constituents (predominantly SO_2 and gaseous H_2SO_4).

The observations were conducted by P. G. Steffes and J. M. Jenkins of Georgia Tech and by M. J. Klein of JPL. Observations of Venus and several calibration sources in the same approximate regions of the sky (DR21, 3C454.3, P-2134 + 004, Jupiter, and 3C123) were made at 8.42 GHz (3.6 cm), 13.3 GHz (2.25 cm), 18.46 GHz (1.63 cm), and 22.2 GHz (1.35 cm) over a four day period from April 25 through April 28, 1987. Observations at 1.63 cm and 2.25 cm were made using the 140-foot diameter NRAO radio telescope at Greenbank, West Virginia. (The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under contract with the National Science Foundation.) Simultaneous observations at 1.35 cm and 3.6 cm were made with the 64-meter diameter DSN antenna at Goldstone, California. It should also be noted that over the entire month of April 1987, daily observations of the 3.6 cm Venus emission were also made with the 34-meter diameter DSN antenna, also located at Goldstone.

The dates of the observations were selected so that Venus would be close enough to superior conjunction so that it would appear as a very small source (approximately 12 arcseconds), but still far enough from the sun to avoid interference. This was done in order to minimize difficulties with beam size correction and source size correction. The times of observation were selected so as to maximize the elevation angle of the observing antennas, and thus minimize the effects of the earth's atmosphere on the observation. Since the microwave emission spectrum of Venus is a continuum, with little narrow line

structure (due to the high atmospheric pressure), wide receiver bandwidths were used, which also served to increase the accuracy of the radiometric measurement. The bandwidths used were 20 MHz (8.42 GHz), 200 MHz (13.3 GHz), 250 MHz (18.46 GHz), and 20 MHz (22.2 GHz). Receiver system noise temperatures of 81 K or less were achieved at all frequencies further increasing the sensitivity of the measurement.

Initial calibration and study of the observed data is complete and we hope to continue further analysis during the next grant year. Effects such as the variation of receiving antenna aperture efficiency with hour angle, declination, and frequency have presented challenging calibration problems, but we believe our frequent observations of reference sources have provided proper correction for these effects. Calibration of the data has been a very time consuming activity, but has resulted in some surprising findings. The results, shown in Figure 7, show a relatively high Venus brightness of 662 K at 3.6 cm, which almost monotonically decreases with decreasing wavelength down to 523 K at 1.63 cm. This included an emission measurement of 565 K at 2.2 cm. Between 1.63 and 1.35 cm, the emission is relatively constant, with a 1.35 cm value of 519 K. Also shown in Figure 7 are computed emission spectra for Venus (Janssen, personal communication). The upper line represents the disk temperature computed by assuming that the only source of microwave opacity in the atmosphere is CO_2 , and uses the CO_2 opacity results from Ho, Kaufman, and Thaddeus (1966) and the Venus temperature-pressure profile from Seiff et al. (1980). The middle line represents the disk temperature computed as above, but also includes the effects of the opacity of a 10 km deep layer of gaseous H_2SO_4 (altitudes from 42 to 52 km) with a mixing ratio of 1 ppm. (The lower line includes the effects of 20 km deep layer, i.e., altitudes from 32 to 52 km).

The opacity from the gaseous sulfuric acid has been newly computed by adding contributions from over 11,800 resonant lines, and by assuming the Van Vleck-Weisskopf lineshape with a broadening parameter of 3 MHz/Torr for all lines. This new attempt at developing a theoretical formulation for the microwave opacity of gaseous sulfuric acid were stimulated by our previous laboratory results (Steffes, 1986). Typical results for the microwave opacity spectrum of gaseous sulfuric acid using this formulation are shown in Figure 8 (Janssen, personal communication) along with results of laboratory measurements under the same conditions (CO_2 atmosphere, $P = 1$ Bar, $T = 575$ K, H_2SO_4 mixing ratio = 0.4%). Comparison of the two results shows a striking correlation in that a peak in opacity occurs near the 2 cm wavelength. Janssen's theoretical formulation differs from the laboratory results in that it indicates an opacity which is greater by a factor of 2 to 3 at the peak, and nearly an order of magnitude greater at longer wavelengths. Some of this apparent variation may be due to mixing ratio uncertainties in the laboratory measurement, since the assumed dissociation factor for H_2SO_4 into SO_3 and H_2O was 0.47, which has never been confirmed by laboratory measurement. This variation may also be partially due to the use of the 3 MHz/Torr broadening parameter for all resonant lines in the theoretical calculation. Another notable difference is the apparent width of the absorptivity peak near 2 cm. Since the laboratory measurements were made only at specific frequencies, the inferred absorption spectrum (solid curve) was developed based on an arbitrary shape. The shape of the curve developed by Janssen, therefore, is still consistent with our results, but it will also affect the range of frequencies or wavelengths over which a depressed disk brightness temperature might be expected.

There are several notable aspects to our results (Figure 7) for the microwave emission from Venus. The first is the relatively high values measured for the brightness temperatures at all wavelengths. Such high values, especially at the shortest wavelengths, suggest a reduced SO_2 abundance in the atmospheric region near the clouds. This may be suggestive of substantial temporal variation in Venus SO_2 abundance since the Pioneer-Venus probe entry. At longer wavelengths (3.6 cm), the higher brightness temperatures suggest increased opacity (possibly due to SO_2) very low in the atmosphere or some variation in surface emission with planetary phase. The second noticeable feature is the nature of the hoped-for dip in emission around 2 cm. A dip on the order of 50 K below the expected value over a narrow wavelength range was thought possible. Instead, we have observed a much shallower dip over a wider wavelength range. This is consistent with the theoretically-derived absorption spectrum of Janssen. Moreover, the shallowness of the dip suggests an average gaseous H_2SO_4 abundance below the clouds of between 1 and 5 ppm, depending on whether the laboratory-based or the theoretically-based values for H_2SO_4 opacity are employed. Additionally, variations in vertical distribution may allow peak abundances which are even larger (15-20 ppm).

It should also be noted that our earth-based observations of the Venus microwave emission are inherently weighted toward the equatorial zones. Thus, variations in gaseous sulfuric acid abundance with latitude are not being resolved, nor are contributions from the polar regions. However, our results suggest that the inferred microwave opacity appears to be lower than that inferred from radio occultation measurements in the 1970s and early 1980s (e.g., Cimino, 1982). These may be suggestive of either large scale temporal

variations in the abundance of gaseous H_2SO_4 or large spatial variation between abundances in polar regions (as inferred from radio occultations) and those in equatorial zones (as inferred from our emission measurements). One important tool for determining which effect is occurring would be reduction of the microwave data from the 1986-87 Pioneer-Venus radio occultation measurements. This data was taken over a wide range of latitudes and could be critical for determining whether temporal variations or spatial variations in gaseous H_2SO_4 abundance could be occurring. Thus, we have discussed with Dr. Arvydas J. Kliore (P-V Radioscience Leader) the possibility of our group obtaining the currently unreduced data and (working at JPL) reducing the data to obtain absorptivity profiles for the 1986-87 epoch. A more complete description of our proposed activity is included in the accompanying proposal.

VI. PUBLICATIONS AND INTERACTION WITH OTHER INVESTIGATORS

At the beginning of the current grant year, a paper was completed and accepted for publication in Icarus, describing results and applications of experiments performed during the previous year of Grant NAGW-533 (Steffes and Jenkins, 1987). This paper is described at length in Section I of this report. More recently, we have submitted summaries of our laboratory measurements for inclusion in the twentieth issue of the Newsletter of Laboratory Spectroscopy for Planetary Science. In November, we presented our most recent results for the laboratory measurements of the millimeter-wave opacity of ammonia under Jovian conditions at the 19th Annual Meeting of the Division of Planetary Sciences of the American Astronomical Society (AAS/DPS Meeting) in a paper by Joiner et al. (1987)*. In a related meeting held in conjunction with

*Abstract attached--See appendices.

the DPS meeting, entitled, "Laboratory Measurements for Planetary Science," we presented a summary of our millimeter-wave laboratory activities, and their application to the interpretation of radio absorptivity data entitled, "Laboratory Measurements of the Millimeter-Wave Absorption from Gaseous Constituents under Simulated Conditions for the Outer Planets" (Steffes, 1987). Also at the AAS/DPS meeting, we presented results of our microwave measurements of the absorptivity of H_2O and CH_4 (Jenkins and Steffes, 1987),* as well as initial results from the 1.3-3.6 cm observation of Venus (Steffes et al., 1987)*. Support for travel by Professor Steffes to Pasadena for both these meetings (and the earlier trip to JPL for analysis of the Venus microwave observations) was provided by Georgia Tech in support of planetary atmospheres research. (It should also be noted that partial support for travel to NRAO for the April 1987 observation was provided by Georgia Tech.) By the end of January (1988), we hope to be able to submit papers on these same subjects to refereed journals (Icarus and Astrophysical Journal) for publication.

In addition to the observations of Venus and analysis work conducted jointly with Dr. Michael J. Klein of JPL, we have also worked closely with Dr. Michael A. Janssen of JPL regarding models for the Venus atmosphere, interpretation of microwave emission measurements, and theoretical models for the absorption spectrum of H_2SO_4 . We have also had productive discussions with Dr. Arvydes J. Kliore regarding our proposed future involvement with the reduction and interpretation of data from recent Pioneer-Venus Radio Occultation Studies. More informal contacts have been maintained with groups at the California Institute of Technology (Dr. Duane O. Muhleman, regarding radio astronomical measurements of Venus opacity), at the Stanford Center for

*Abstracts attached--See Appendices

Radar Astronomy (V. R. Eshleman, G. L. Tyler, and D. P. Hinson, regarding Voyager results for the outer planets, and laboratory measurements), and at JPL (Drs. Robert Poynter and Samuel Gulkis, regarding radio astronomical observations of the outer planets and Venus). We have also been active in the review of proposals submitted to the Planetary Atmospheres Program at NASA and as a reviewer of manuscripts submitted to Icarus and the Journal of Geophysical Research, for which Dr. Steffes is an Associate Editor. Another source of close interaction with other planetary atmospheres principal investigators has been Dr. Steffes' membership in the Planetary Atmospheres Management and Operations Working Group (PAMOWG). Travel support for attendance at PAMOWG meetings has been provided by Georgia Tech.

VII. CONCLUSION

Over this past grant year, we have continued to conduct laboratory measurements of the microwave properties of atmospheric gases under simulated conditions for the outer planets. A most significant addition to this effort has been our capability to make such measurements at longer millimeter-wavelengths (7-10 mm). In the future, we hope to extend such measurements to even shorter millimeter-wavelengths. We will likewise continue to pursue further analysis and application of our laboratory results to microwave and millimeter-wave absorption data for the outer planets, such as results from Voyager Radio Occultation experiments and earth-based radio astronomical observations. We also intend to pursue the analysis of available multi-spectral microwave opacity data from Venus, including data from our most recent radio astronomical observations in the 1.3-3.6 cm wavelength range and Pioneer-Venus Radio Occultation measurements at 13 and 3.6 cm, using our

previous laboratory measurements as an interpretive tool. The timely publication of all of these results will be a high priority.

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IX. KEY FIGURES

Table I

Absorption Summary for 1.6 GHz

Date	Temperature K	Mixing Ratio	Pressure (atm.)	α (dB/km) Measured	α (dB/km) Theoretical
9/25/86	206	3.7×10^{-3}	6.1	1.273 ± 1.0	1.35
			4.1	0.0 ± 1.0	0.66
			2.0	0.0 ± 1.0	0.18
9/17/86	193	3.7×10^{-3}	6.1	1.83 ± 1.8	1.58
			4.1	0.92 ± 1.3 -0.9	0.78
			2.0	0.46 ± 1.4 -0.5	0.21

TABLE II

Absorption Summary for 2.2 GHz

Date	Temperature K	Mixing Ratio	Pressure (atm.)	α (dB/km) Measured	α (dB/km) Theoretical
8/6/86	300	3.7×10^{-3}	6.1	0.91 ± 0.27	0.89
			4.1	$0.36 \begin{smallmatrix} +0.28 \\ -0.27 \end{smallmatrix}$	0.42
			2.0	$0.27 \begin{smallmatrix} +0.28 \\ -0.27 \end{smallmatrix}$	0.11
7/25/86	193	3.7×10^{-3}	6.1	1.73 ± 0.27	2.58
			4.1	0.91 ± 0.18	1.23
			2.1	0.50 ± 0.18	0.34
8/13/86	193	3.7×10^{-3}	6.1	$2.10 \begin{smallmatrix} +0.27 \\ -0.28 \end{smallmatrix}$	2.58
			4.1	0.82 ± 0.23	1.23
			2.0	$0.37 \begin{smallmatrix} +0.18 \\ -0.19 \end{smallmatrix}$	0.34
9/17/86	193	3.7×10^{-3}	6.1	$2.19 \begin{smallmatrix} +0.22 \\ -0.23 \end{smallmatrix}$	2.58
			4.1	$1.28 \begin{smallmatrix} +0.22 \\ -0.23 \end{smallmatrix}$	1.23
			2.0	$0.37 \begin{smallmatrix} +0.22 \\ -0.23 \end{smallmatrix}$	0.34
7/14/86	178	4.3×10^{-4}	6.1	$0.18 \begin{smallmatrix} +0.28 \\ -0.18 \end{smallmatrix}$	0.36
			3.2	$0.18 \begin{smallmatrix} +0.22 \\ -0.13 \end{smallmatrix}$	0.11

TABLE III

Absorption Summary for Ammonia at 203K

Mixing Ratio = 0.0184

Date	Frequency (GHz)	Pressure (atm)	(dB/km) Measured	(dB/km) VVW	(dB/km) BR
<hr/>					
10/9/87	32.15	2	327.6 \pm 227	462.6	343.5
10/9/87	32.15	1	109.3 \pm 118	173.9	130.2
10/13/87	32.15	2	382.2 \pm 227	462.6	343.5
10/13/87	32.15	1	109.1 \pm 118	173.9	130.2
9/24/87	36.24	2	364.2 \pm 82	351.4	234.1
9/24/87	36.24	1	91.2 \pm 73	100.2	73.5
10/9/87	36.24	2	327.8 \pm 227	351.4	234.1
10/9/87	36.24	1	109.3 \pm 118	100.2	73.5
10/13/87	36.24	2	273.3 \pm 91	351.4	234.1
10/13/87	36.24	1	36.5 \pm 73	100.2	73.5
9/24/87	36.95	2	327.7 \pm 82	336.8	220.1
9/24/87	36.95	1	63.7 \pm 63	93.9	67.7
10/9/87	38.99	2	255.0 \pm 109	300.8	182.1
10/9/87	38.99	1	72.9 \pm 109	87.0	53.4
10/13/87	38.99	2	164.0 \pm 82	300.8	182.1
10/13/87	38.99	1	72.9 \pm 72	87.0	53.4
9/24/87	39.13	2	291.2 \pm 82	298.8	184.6
9/24/87	39.13	1	109.1 \pm 64	86.8	45.5
10/9/87	39.66	2	145.6 \pm 82	289.6	172.5
10/9/87	39.66	1	54.6 \pm 54	83.1	50.2
10/13/87	39.66	2	164.0 \pm 82	289.6	172.5
10/13/87	39.66	1	18.3 \pm 73	83.1	50.2
9/24/87	39.86	2	182.2 \pm 54	288.0	174.8
9/24/87	39.86	1	72.9 \pm 54	81.3	50.6

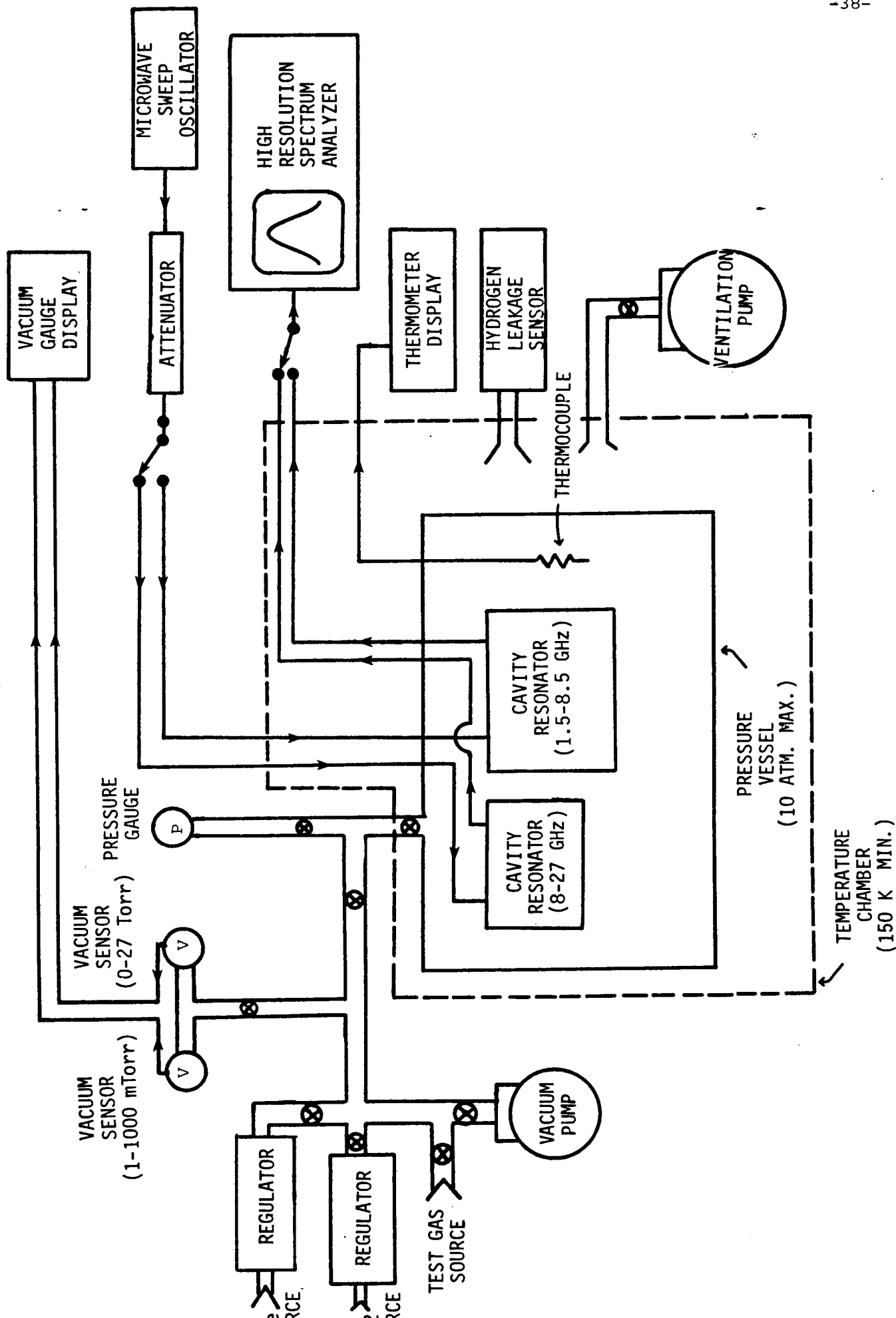


Figure 1: Block diagram of atmospheric simulator, as configured for measurements of the microwave absorption from test gases under simulated conditions for the outer planets.

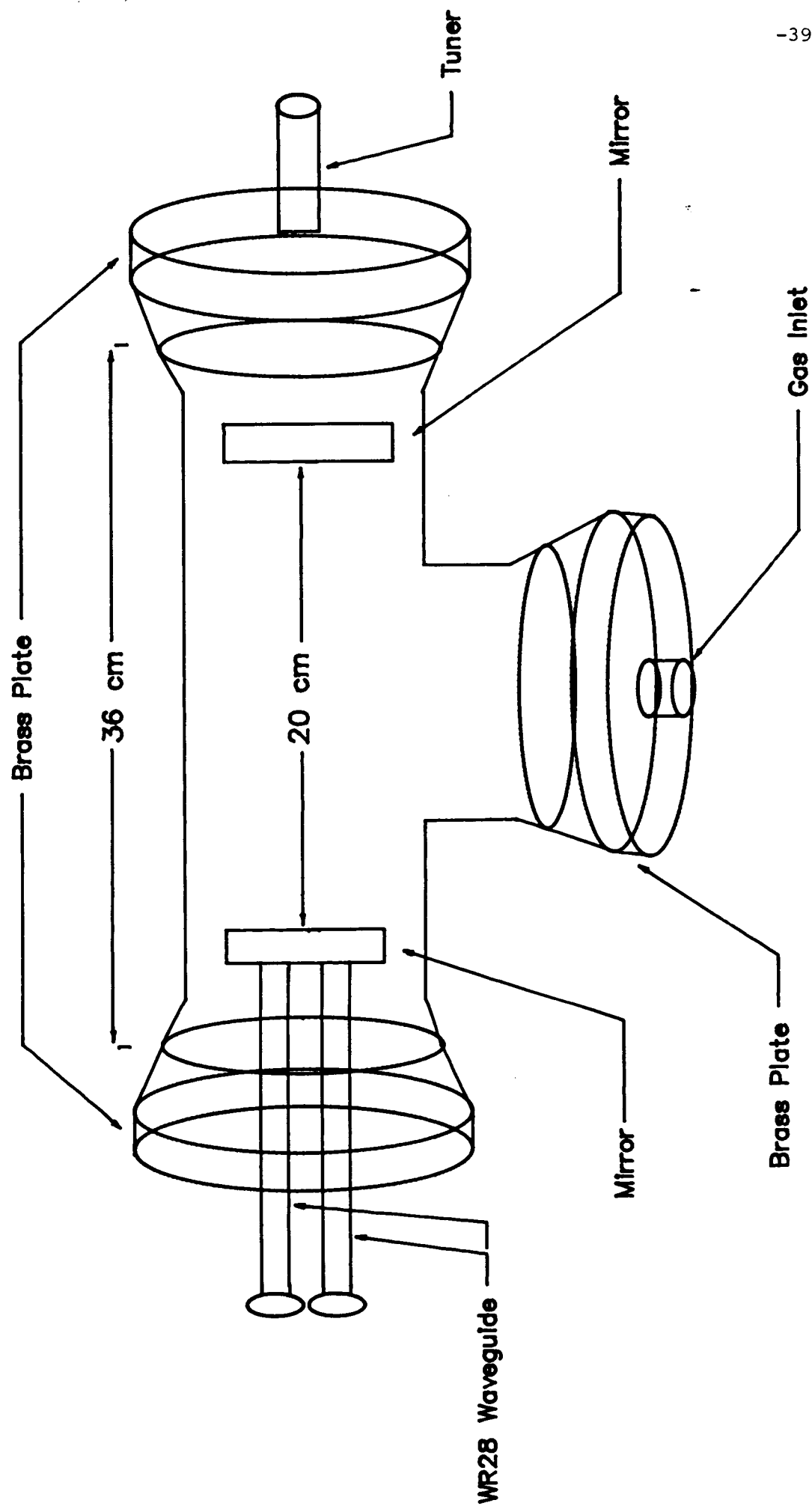


Figure 2: Diagram of Fabry-Perot Resonator

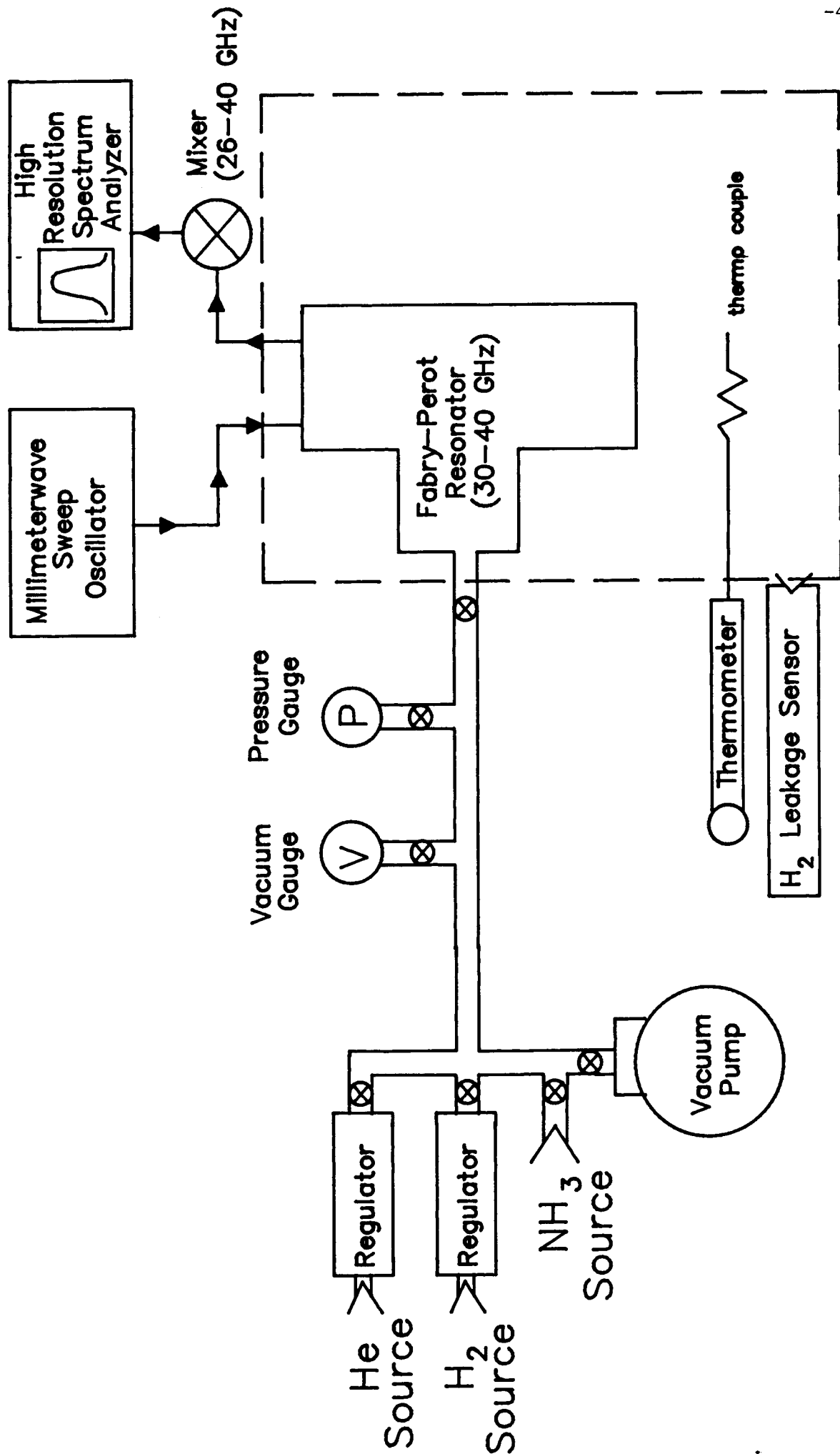
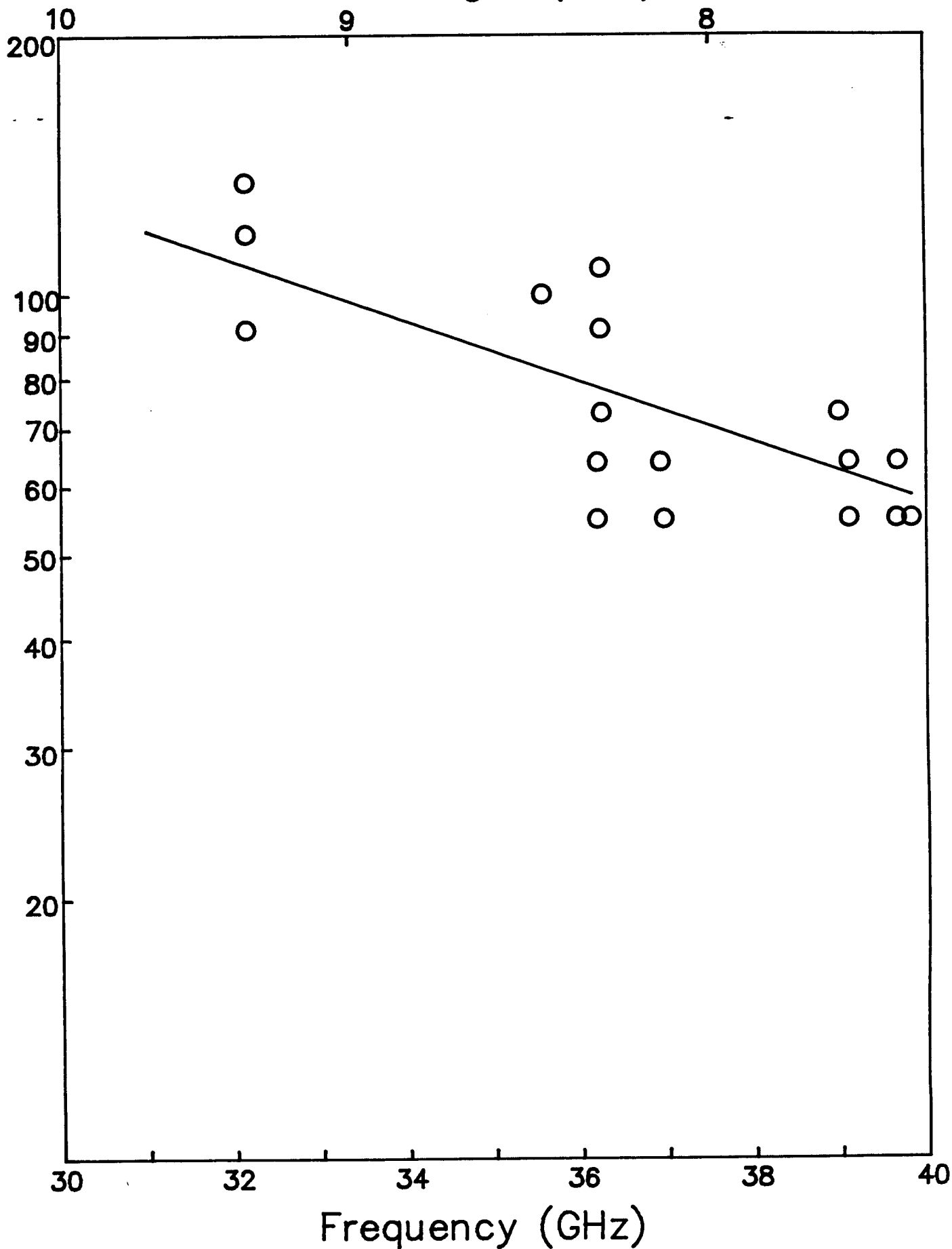


Figure 3: Block Diagram of Atmospheric Simulator (mm-wave)

Figure 4: Minimum detectable absorptivities for the planetary atmospheres simulator under simulated Jovian conditions ($T=200$ K). Variations at individual frequencies are due to resonator adjustments. (Solid line is average.)

Minimum Detectable Absorptivity of Gas Mixture (dB/km)



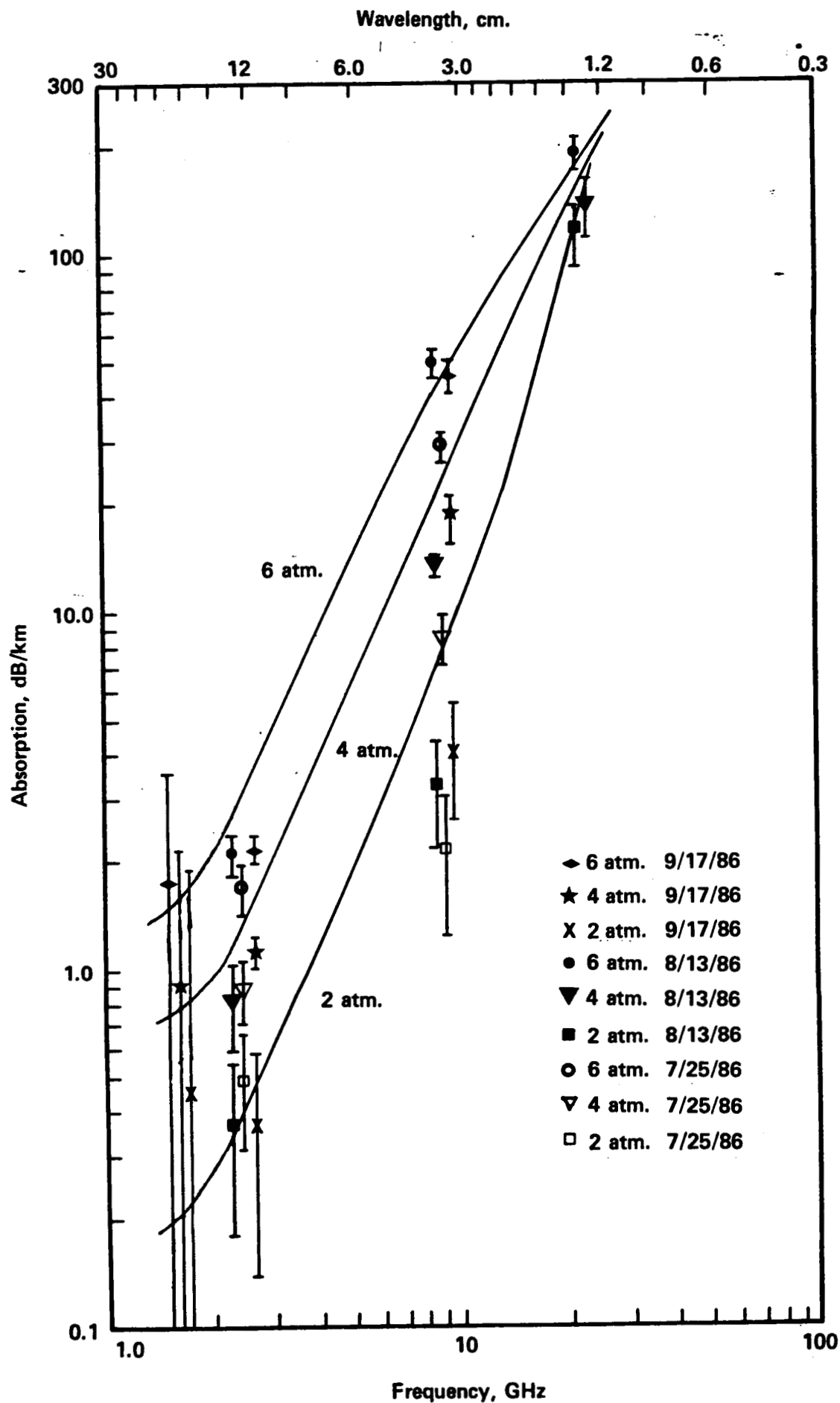


Figure 5: Measured microwave absorption from gaseous ammonia ($3.7 \pm 0.8 \times 10^{-3}$, by volume) in a 90% hydrogen/10% helium atmosphere as a function of frequency (wavelength), at 193 ± 8 K, at three different pressures. Also shown (solid lines), are theoretically derived absorption profiles.

Absorption of NH_3
in a 90% H_2 10% He atmosphere
(Mixing Ratio: 0.0184 Pressure: 2 atm.)

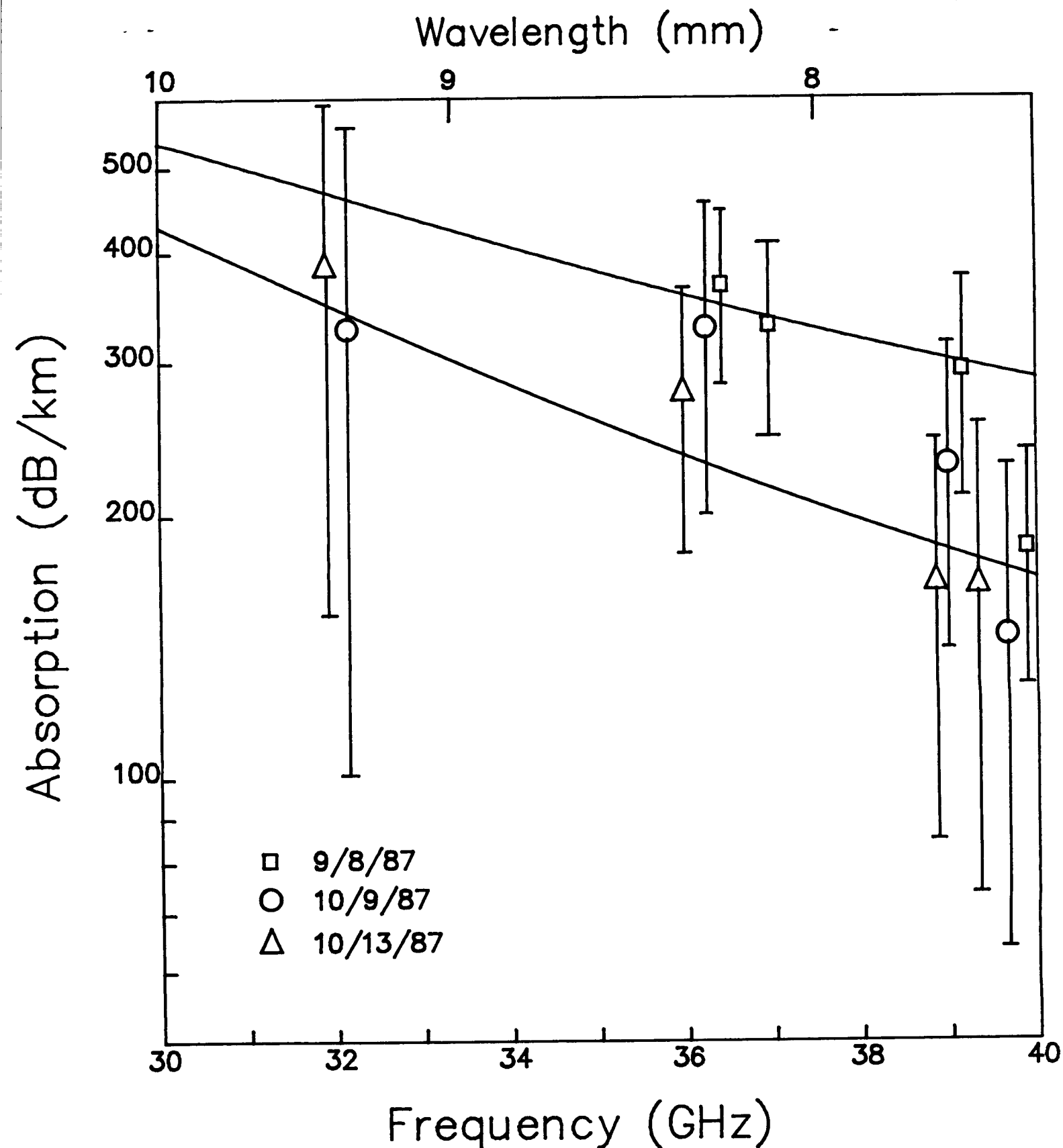


Figure 6: Ammonia absorption under Jovian conditions ($T=203$ K).

VENUS MICROWAVE EMISSION SPECTRUM

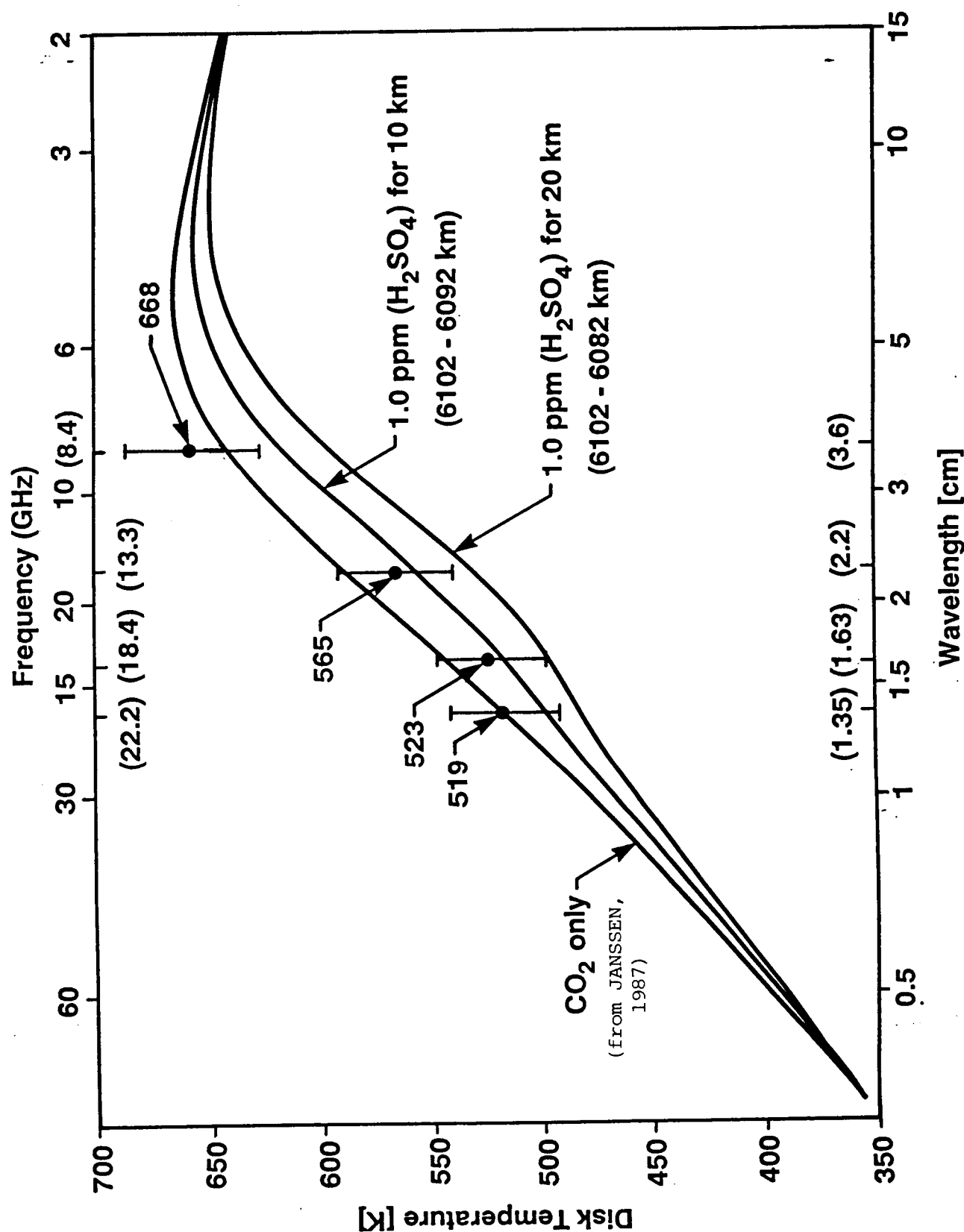


Figure 7: Microwave emission measurements of Venus expressed as average disk brightness temperatures (assumed disk radius is 6100 km) for measurements made in April 1987. Solid lines are computed emission spectra from a model by Janssen (personal communication, 1987.)

X. APPENDICES

AMERICAN ASTRONOMICAL SOCIETY SPECIAL ABSTRACT FORM

Laboratory Measurements of the Opacity of Gaseous Ammonia (NH₃) in the 7.3-8.3 mm (36-41 GHz) Range Under Simulated Conditions for Jovian Atmospheres

J. Joiner, J. M. Jenkins, P. G. Steffes (Georgia Institute of Technology)

Previous experimental results have verified that the modified Ben-Reuven lineshape correctly describes the opacity of gaseous ammonia (NH₃) in an H₂/He atmosphere at wavelengths from 1.38 to 18.5 cm (1.62-21.7 GHz). To determine whether the Ben-Reuven lineshape correctly describes the absorption spectrum of NH₃ at wavelengths shortward of 1 cm, laboratory measurements of the opacity of NH₃ in a 90% H₂/10% He atmosphere at pressures up to 2 atm and at wavelengths from 7.3-8.3 mm (36-41 GHz) have been made at room temperature. Further measurements in the same frequency and pressure ranges are presently being made at temperatures as low as 193K. These measurements are needed for inferring the abundance and distribution of NH₃ in the upper atmospheres of the outer planets from radio astronomical observations at these wavelengths.

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Limits of the Microwave Absorption of H_2O and CH_4 in the Jovian Atmosphere

J. M. Jenkins, P. G. Steffes (Georgia Institute of Technology)

The modified Ben-Reuven lineshape used to model the microwave absorption of gaseous ammonia (NH_3) in a Jovian atmosphere suggests that the absorption due to a solar abundance of NH_3 (150 ppm) is not large enough to account for the actual absorption from 10 to 20 cm as inferred by the recent spectral emission studies and radio occultation experiments. To determine whether there is an additional microwave absorbing constituent present in Jupiter's atmosphere, we have measured the microwave absorption of methane (CH_4) and water vapor (H_2O) in a simulated Jovian atmosphere at 2.25 GHz (13.3 cm), 8.5 GHz (3.5 cm) and 21.7 GHz (1.38 cm). The measurements of the opacity of CH_4 were conducted at 153 K under pressures as high as 6 atmospheres in various proportions of hydrogen (H_2) and helium (He). The measurements of the opacity of H_2O were made at 298 K under pressures as high as 6 atmospheres in a 90% H_2 /10% He atmosphere with a mixing ratio of 3.5×10^{-3} . The results of these measurements are consistent with the theoretical expressions for microwave opacity in the Jovian atmosphere at the specified frequencies, and suggest that CH_4 and H_2O are not responsible for the additional absorption observed between 10 and 20 cm. Thus ammonia abundances significantly greater than solar abundance are indicated.

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Observation of the Microwave Emission Spectrum of Venus from 1.3 to 3.6 cm

P. G. Steffes, J. M. Jenkins (Georgia Institute of Technology), M. J. Klein (JPL-Caltech)

Previous laboratory measurements have suggested that the intensity and shape of the 1.3-3.6 cm Venus emission spectrum would be especially sensitive to the sub-cloud abundance of constituents such as SO₂ and gaseous H₂SO₄. It was likewise suggested that some variations of the shape of the emission spectrum might occur between 1.5 and 3 cm (10 to 20 GHz), a wavelength range which had previously only been sparsely observed. As a result, coordinated observations of Venus emission were conducted at 1.35 cm (22.2 GHz) and 3.6 cm (8.42 GHz) using the 64-meter DSN antenna at Goldstone, CA and at 1.63 cm (18.46 GHz) and 2.25 cm (13.3 GHz) using the 42-meter NRAO antenna at Greenbank, WV.* Observations at the two sites were conducted within 2 weeks of each other. Receiver noise temperatures between 25 K and 81 K were achieved at all wavelengths, and special attention was paid to correcting for variations in antenna aperture efficiency and in the Earth's atmospheric opacity.

The results of these observations allow us not only to place limits on the abundance and distribution of SO₂ and gaseous H₂SO₄, but to also infer limits to variations of the abundance of such constituents since the 1978 Pioneer-Venus encounter.

- * The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under contract with the National Science Foundation. This work was supported in part by NASA Grant NAGW-533.

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